



## Detection of the Crab Pulsar with VERITAS above 100 GeV

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**Abstract:** We discuss the recent detection of pulsed gamma-ray emission from the Crab Pulsar above 100 GeV with the VERITAS array of atmospheric Cherenkov telescopes. Gamma-ray emission at these energies is not expected in present pulsar models. We find that the photon spectrum of pulsed emission between 100 MeV and 400 GeV can be described by a broken power law, and that it is statistically preferred over a power law with an exponential cut-off. In the VERITAS energy range the spectrum can be described with a simple power law with a spectral index of -3.8 and a flux normalization at 150 GeV that is equivalent to 1% of the Crab Nebula gamma-ray flux. The detection of pulsed emission above 100 GeV and the absence of an exponential cutoff rules out curvature radiation as the primary gamma-ray-producing mechanism. The pulse profile exhibits the characteristic two pulses of the Crab Pulsar at phases 0.0 and 0.4, albeit 2-3 times narrower than below 10 GeV. The narrowing can be interpreted as a tapered particle acceleration region in the magnetosphere. Our findings require that the emission region of the observed gamma rays be beyond 10 stellar radii from the neutron star.

**Keywords:** VHE, gamma-rays, pulsar, Crab, VERITAS

## 1 Introduction

One of the most powerful pulsars in gamma rays is the Crab Pulsar [1, 2], PSR J0534+220, which is the remnant of a historical supernova that was observed in 1054 A.D. It is located at a distance of 6500 light years, has a rotation period of  $\approx 33$  ms, a spin-down power of  $4.6 \times 10^{38}$  erg s $^{-1}$  and a surface magnetic field of  $3.78 \times 10^{12}$  G [3].

Within the corotating magnetosphere, charged particles are accelerated to relativistic energies and emit non-thermal radiation from radio waves through gamma rays. In general, gamma-ray pulsars exhibit a break in the spectrum between a few hundred MeV and a few GeV. Mapping the cut-off can help to constrain the geometry of the acceleration region, the gamma-ray radiation mechanisms and the attenuation of gamma-rays. Based on previous measurements and present theoretical understanding that the dominant gamma-ray emission mechanism is curvature radiation, it is widely believed that the shape of the spectral break is best described by an exponential cut-off.

Although measurements of the Crab Pulsar spectrum are consistent with a power law with exponential cut-off, flux measurements above 10 GeV are systematically above the best-fit model, suggesting that the spectrum is indeed harder than a power law with exponential cut-off [2, 4]. However, the statistical uncertainty of the previous data was insufficient to allow a definite conclusion about the spectral shape. In this paper we summarise the recent detection of the Crab Pulsar above 100 GeV with VERITAS

that rules out that the spectrum above the break is described by an exponential cut-off. In Section 2 we describe the observation and analysis. The results are presented in Section 3 and we close the paper with a discussion in Section 4.

## 2 Observation and analysis

VERITAS, the Very Energetic Radiation Imaging Telescope Array System, is an array of four, 12 m diameter imaging atmospheric Cherenkov telescopes located in southern Arizona, USA [5]. After evidence for pulsed emission was seen in 45 hours of data from the Crab Pulsar that were recorded between 2007 and 2010, a deep 62-hour observation was carried out on the Crab Pulsar between September 2010 and March 2011. The observations were made in wobble mode with a 0.5 degree offset. After eliminating data taken under variable or poor sky conditions or affected by technical problems, the total analysed data set comprises 107 hours of observations (97 hours dead-time corrected) carried out with all four telescopes. The data were taken with the standard VERITAS trigger setting, and analysed with the standard VERITAS analysis tools.

### 2.1 Event Reconstruction

In the analysis, the recorded atmospheric shower images are processed with a standard moment analysis [6] and the energy and arrival direction of the primary particle are cal-

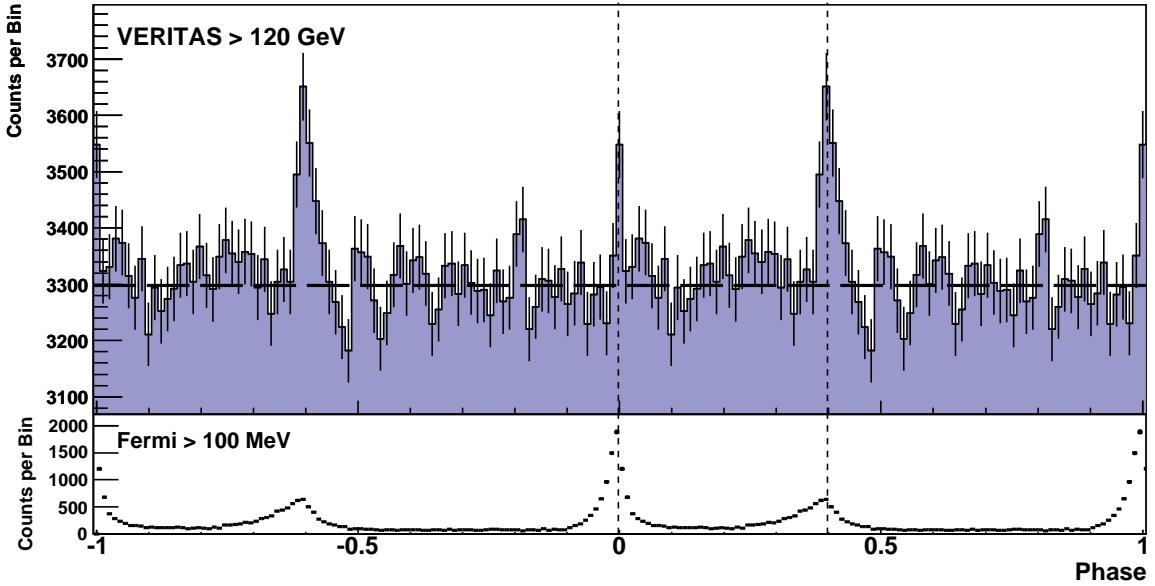


Figure 1: VERITAS pulse profile of the Crab Pulsar at  $> 120$  GeV. The shaded histograms show the VERITAS data. The pulse profile is shown twice for clarity. The dashed horizontal line shows the background level estimated from data in the phase region between 0.43 and 0.94. The data above 100 MeV from the Fermi-LAT [2] are shown beneath the VERITAS profile. The vertical dashed lines in the panels mark the best-fit peak positions of P1 and P2 in the VERITAS data.

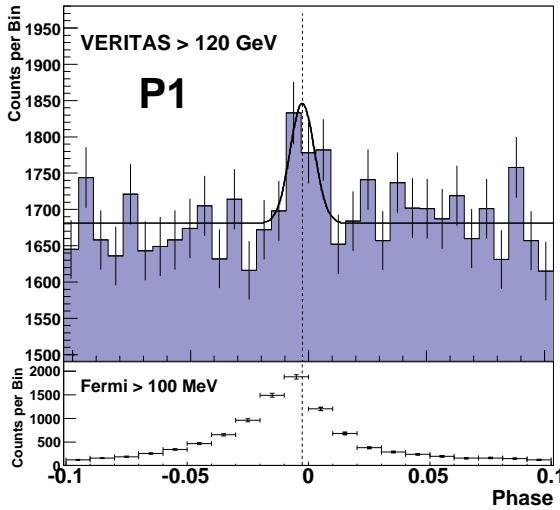


Figure 2: Enlarged view of the main pulse or P1 of the Crab Pulsar pulse profile. See text.

culated [7]. After event reconstruction, a selection is performed to reject events caused by charged cosmic rays. The selection criteria were optimised *a priori* for highest sensitivity by assuming a simple power-law energy spectrum for the Crab Pulsar with an index  $\alpha = -4$  and a flux normalisation of a few percent of the Crab Nebula flux at 100 GeV. The analysis threshold is 120 GeV.

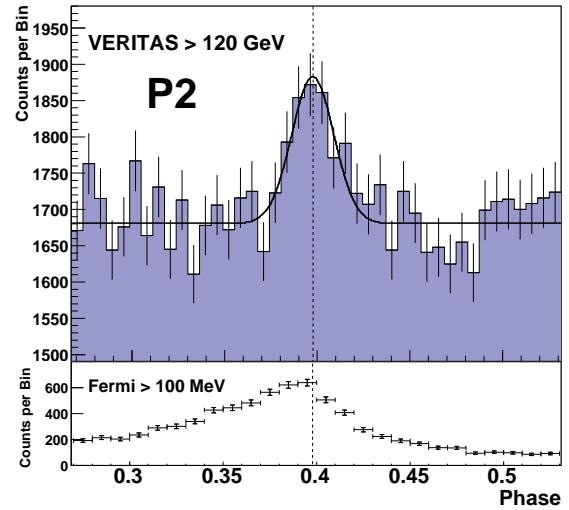


Figure 3: Enlarged view of the interpulse or P2 of the Crab Pulsar pulse profile. See text.

For the pulsar analysis, the arrival times of the selected events are transformed to the barycenter of the solar system. After barycentering, the phase of the Crab Pulsar is calculated for each event using contemporaneous ephemerides of the Crab Pulsar that are published monthly by the Jodrell Bank telescope [8].

The results were confirmed by a separate analysis of the data made using an independent analysis package.

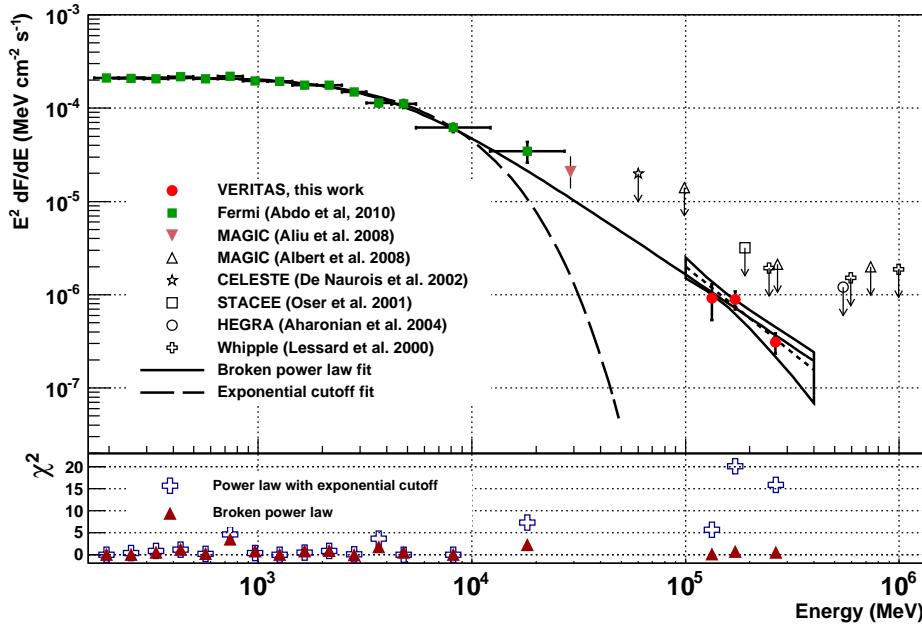


Figure 4: Spectral energy distribution (SED) of the Crab Pulsar in gamma rays. VERITAS flux measurements are shown by the solid red circles, Fermi-LAT data [2] by green squares, and the MAGIC flux point [4] by the solid triangle. The empty symbols are upper limits from CELESTE, MAGIC, and Whipple. The bow tie and the enclosed dotted line give the statistical uncertainties and the best-fit power-law spectrum for the VERITAS data using a forward-folding method. The result of a fit of the VERITAS and Fermi-LAT data with a broken power law is given by the solid line and the result of a fit with a power-law spectrum multiplied with an exponential cut-off is given by the dashed line. Below the SED we plot  $\chi^2$  values to visualise the deviations of the best-fit parametrisation from the Fermi-LAT and VERITAS flux measurements.

### 3 Results

#### 3.1 Pulse Profile

The phase-folded event distribution, hereafter pulse profile, of the selected VERITAS events is shown in Figure 1. The most significant structures are two pulses with peak amplitudes at phase 0.0 and phase 0.4. These coincide with the locations of the main pulse and interpulse, hereafter P1 and P2, which are the two main features in the pulse profile of the Crab Pulsar throughout the electromagnetic spectrum. In order to assess the significance of the pulsed emission, we use the H-Test [9]. The test result is 50, which translates into a statistical significance of 6.0 standard deviations that pulsed emission is present in the data.

The pulse profile has been characterised by an unbinned maximum-likelihood fit; see the solid black line in Figures 2 and 3. In the fit, the pulses are modeled with Gaussian functions, and the background is determined from the events that fall between phases 0.5 and 0.9 in the pulse profile (referred to as the off-pulse region).

The positions of P1 and P2 in the VERITAS data are thus determined to lie at the phase values  $-0.0026 \pm 0.0028$  and  $0.3978 \pm 0.0020$ , respectively and are shown by the vertical lines Figure 1. The full widths at half maximum (FWHM) of the fitted pulses are  $0.0122 \pm 0.0035$  and  $0.0267 \pm 0.0052$ , respectively. The pulses are narrower

than those measured by Fermi-LAT at 100 MeV by a factor of two to three. The energy-dependent narrowing of the pulses is a strong probe of the nature of the magnetospheric particle acceleration region and can be used to shed some light on its geometry, electric field, and gamma-ray emission properties. If gamma rays observed at the same phase are emitted by particles that propagate along the same magnetic field line [10], then a possible explanation of the observed narrowing is that the region where acceleration occurs tapers towards the neutron star. However, detailed calculations are necessary to explain fully the observed pulse profile.

#### 3.2 Spectral differences between P1 and P2

Along with the observed differences in the pulse width, the amplitude of P2 is larger than P1 in the profile measured with VERITAS, in contrast to what is observed at lower gamma-ray energies where P1 dominates (see Figure 1). It is known that the ratio of the pulse amplitudes changes as a function of energy above 1 GeV [2] and becomes near unity for the pulse profile integrated above 25 GeV [4].

In order to quantify the relative intensity of the two peaks above 120 GeV, we integrate the excess between phase  $-0.013$  and  $0.009$  for P1 and between  $0.375$  and  $0.421$  for P2. This is the  $\pm 2$  standard deviation interval of each pulse

as determined from the maximum-likelihood fit. The significance of the excess in these regions is 4.7 standard deviations for P1 and 7.9 standard deviations for P2. The ratio of the excess events and thus the intensity ratio of P2/P1 is  $2.4 \pm 0.6$ . If one assumes that the differential energy spectra of P1 and P2 above 25 GeV can each be described with a power law,  $dN/dE \propto E^\alpha$ , and that the intensity ratio is exactly unity at 25 GeV [4], then the spectral index  $\alpha$  of P1 must be smaller than the spectral index of P2 by  $\alpha_{\text{P2}} - \alpha_{\text{P1}} = 0.56 \pm 0.16$ .

### 3.3 Phase-averaged spectrum

The gamma-ray spectrum above 100 GeV was measured by combining the signal regions around P1 and P2 defined above. This can be considered a good approximation of the phase-averaged spectrum since no “bridge emission”, which is observed at lower energies, is seen between P1 and P2 in the VERITAS data. However, the existence of a flux component that originates in the magnetosphere and is uniformly distributed in phase cannot be excluded and would be indistinguishable from the gamma-ray flux from the nebula. Figure 4 shows the VERITAS phase-averaged spectrum together with measurements made with Fermi-LAT and MAGIC. In the energy range between 100 GeV and 400 GeV measured by VERITAS, the energy spectrum is well described by a power law  $dN/dE = A \times (E/150 \text{ GeV})^\alpha$ , with  $A = (4.2 \pm 0.6_{\text{stat}} + 2.4_{\text{syst}} - 1.4_{\text{syst}}) \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$  and  $\alpha = -3.8 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}}$ . The detection of pulsed gamma-ray emission between 200 GeV and 400 GeV, the highest energy flux point, is only possible if the emission region is at least 10 stellar radii from the star’s surface [11].

### 3.4 The spectral energy distribution between 100 MeV and 300 GeV

Combining the VERITAS data with the Fermi-LAT data we can place a stringent constraint on the shape of the spectral turnover. The previously favoured spectral shape of the Crab Pulsar above 1 GeV was an exponential cut-off  $dN/dE = A \times (E/E_0)^\alpha \exp(-E/E_C)$ , which is a good parametrisation of the Fermi-LAT [2] and MAGIC [4] data. We note that the Fermi-LAT and MAGIC data can be equally well parametrised by a broken power law but those data are not sufficient to distinguish significantly between a broken power law and an exponential cut-off. The VERITAS data, on the other hand, clearly favour a broken power law as a parametrisation of the spectral shape. The fit of the VERITAS and Fermi-LAT data with a broken power law of the form  $A \times (E/E_0)^\alpha / [1 + (E/E_0)^{\alpha-\beta}]$  results in a  $\chi^2$  value of 13.5 for 15 degrees of freedom with the fit parameters  $A = (1.45 \pm 0.15_{\text{stat}}) \times 10^{-5} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $E_0 = 4.0 \pm 0.5_{\text{stat}} \text{ GeV}$ ,  $\alpha = -1.96 \pm 0.02_{\text{stat}}$  and  $\beta = -3.52 \pm 0.04_{\text{stat}}$  (see solid black line in Figure 2). A corresponding fit with a power law and an exponential cut-off yields a  $\chi^2$  value of 66.8 for 16 degrees of freedom.

The fit probability of  $3.6 \times 10^{-8}$  derived from the  $\chi^2$  value excludes the exponential cut-off as a viable parametrisation of the Crab Pulsar spectrum.

## 4 Discussion

The detection of pulsed gamma-ray emission above 100 GeV provides strong constraints on the gamma-ray radiation mechanisms and the location of the acceleration regions. For example, the shape of the spectrum above the break can not be attributed to curvature radiation because that would require an exponentially shaped cut-off. Assuming a balance between acceleration gains and radiative losses by curvature radiation, the break in the gamma-ray spectrum is expected to be at  $E_{br} = 24 \text{ GeV} \eta^{3/4} \sqrt{\xi}$ , where  $\eta$  is the acceleration efficiency ( $\eta < 1$ ) and  $\xi$  is the radius of curvature in units of the light-cylinder radius [12]. Though  $\xi$  can be larger than one, only with an extremely large radius of curvature would it be possible to produce gamma-ray emission above 100 GeV with curvature radiation. It is, therefore, unlikely that curvature radiation is the dominant production mechanism of the observed gamma-ray emission above 100 GeV. Two possible interpretations are that either the entire gamma-ray production is dominated by one emission mechanism different from curvature radiation or that a second mechanism becomes dominant above the spectral break energy.

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